Mass transport modelling to assess contamination of a water supply well in Sabarmati river bed aquifer, Ahmedabad City, India

V.V.S. Gurunadha Rao · S.K. Gupta

Abstract Drinking water supply wells were constructed in the Sabarmati river bed aquifer of Ahmedabad city using radial pipes and are known as French Collector wells. Contamination of groundwater from one of the French wells near Sabarmati railway bridge was noticed in 1992. The suspected pollution sources are Duff-nala of Shahibaug and two other sources from slum dwellings on either side of Sabarmati river. A combined groundwater flow, pathlines and a mass transport model was constructed covering an area of 9 km^2 to analyse the capture zone of the French well under two different scenarios. Aquifer parameters of the river bed aquifer were available. Dry river bed condition was simulated under scenario I and controlled flow in the river bed was simulated under scenario II. The groundwater velocity and migration of contaminant particles from sources was analysed in the pathline model. Total dissolved solids (TDS) concentration contours originating from sources in the mass transport model (MT3D) were computed by solving an advection-dispersion equation. The computed pathlines and TDS concentration contours indicate likely migration of contaminant plume from pollutant sources to the French well during 365 days under two scenarios. The model results confirm the tracer injection studies carried out to know the likely migration of contaminants towards the French well. The modelling study emphasised the necessity of controlled release of surface water in Sabarmati river bed from Dharoi reservoir throughout the year.

Key words Flow model · Mass transport · Pathlines · Groundwater velocity · Sabarmati river · French collector well · Dry river bed · Tracer

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Introduction

Ahmedabad city (23°02′N, 72°36′E) is situated on the banks of Sabarmati river about 80 km north of the Gulf of Cambay in Gujarat state, India. The city has a total area of about 93 km^2 with a population of over 3 million. The average annual discharge of Sabarmati river at Ahmedabad was about 600×103 million litres before the construction of Dharoi reservoir during 1978. More then 75% of the discharge occurred during the monsoon period. Controlled releases from the reservoir presently ensure an annual average flow of about 600 million litres. The water supply to the city is about 439 million litres per day (MLD), out of which approximately 20 million litres is drawn from the five French (collector) wells located in the river bed at Kotarpur, Bhadreshwar, Camp Hanuman, Acher and Sabarmati Railway bridge. The other important sources of water supply to the city are through tube wells of about 372 MLD; infiltration wells in the river bed of about 47 MLD and surface water from the river through Dudheshwar water works when there is flow in the river.

French wells are radial collector wells with several horizontal radial infiltration pipes emanating from a central caisson (also called jack well) and under favourable hydrogeologcial conditions are a convenient means of groundwater recovery. Five such wells have supplied drinking water from the Sabarmati river bed aquifer during the last decade. Each well pumps at a rate of 4000 m^3/day. Bacterial and fungal contamination was detected in the French well water near Sabarmati railway bridge in Ahmedabad during September 1992 (Figs. 1 and 2). National Environmental Engineering Research Institute (NEERI) and the Nagpur and Physical Research Laboratory (PRL) in Ahmedabad jointly investigated the contamination problem [Draft Final Report (DFR) 1994]. The contamination problem could have been due to infiltration of the river water containing sewage effluent discharged in this reach of Sabarmati river. They have carried out three types of investigations:

1. a tracer test designed to ascertain if there existed a rapid channel type of flow between the sewage discharge points and any of radials of the collector wells
2. a step draw-down pumping and recovery test to understand process of the French well–river-bed aquifer interaction, and

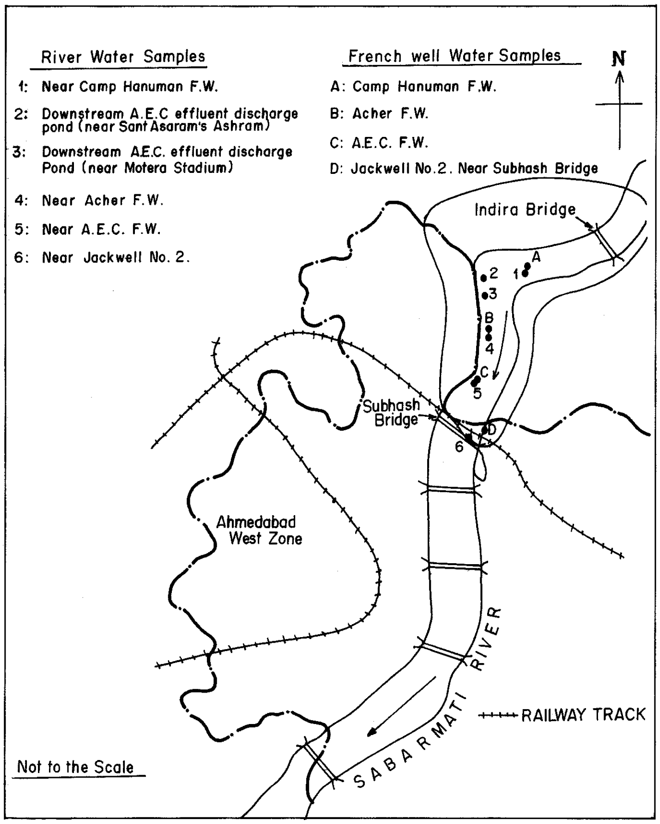

Fig. 1
Water-quality monitoring stations along Sabarmati river in Ahmedabad City

3. physico-chemical and bacteriological analyses of the river-bed aquifer soil samples to ascertain the extent of river bed contamination.

It was reported that observed contamination of water pumped from the collector well was not caused by any channel type of flow. It may be due to slow and steady migration of contaminants over years of persistent sewage effluent discharge from river banks. The groundwater flow, pathline and mass transport models were developed to analyse reported concepts and to verify the results of a field experiment carried out by computing groundwater velocities and studying migration of contaminants from sources in the river bed aquifer. Predictions were made to determine the capture zone of the French well under two scenarios

1. when the river bed was dry with only later groundwater inflow/outflows across the river bed cross-section (scenario I)
2. under controlled release of surface water from upstream Dharoi reservoir to keep a minimum water column of 0.2 m in the Sabarmati river (scenario II).

The problem

Bacterial and fungal contamination was detected in the French well located near the Sabarmati Railway bridge during 1992. As a result, withdrawal of water from this source had to be discontinued resulting in a curtailment of water supply to the city. Each of the French wells comprises of 16 horizontal, radial, collector-pipes to tap the sub-surface water of the Sabarmati river. The collector pipes are placed in two tiers in the river bed (eight at each level)at depths of 10 m and 11 m. The radial collector pipes discharge into the central well from where water is pumped with the help of submersible pumps into the trunk main. The river bed in the vicinity of the French well is about 500 m wide. The collector well is located close to the right bank.

The reconnaissance survey revealed that there are two potential sources of pollution from Shahibaug Duff nala, about 600 m from the French well on the left bank of river discharging a maximum of about 40 MLD domestic waste into the river and a slum pocket on the right bank of the river also discharging domestic waste into the river at a distance of about 100 m upstream of the collector

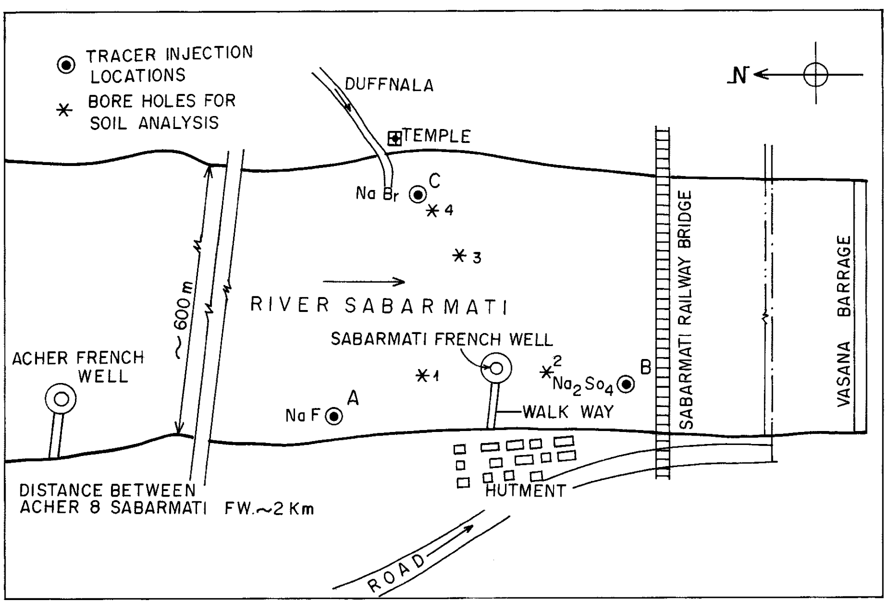

Fig. 2
Location of Sabarmati French well near railway bridge and three sewage (pollutant) sources

well (Fig. 1). The latter flow is very small, about 0.3 MLD. The possibility of contamination due to ponded water in the river downstream was also taken into consideration as some waste water is discharged into the river at several points between the collector well and the Vasana barrage.

Tracer tests

In order to identify the characteristics of subsoil flow and to delineate possible travel path of pollutants originating from the suspected sources to the collector well, tracer studies were carried out. Three chemicals, Sodium Bromide (NaBr), Soidum Fluoride (NaF) and Sodium Sulphate (Na_2SO_4) – (giving Br^-, F^- and SO_4^{2-} ions as tracers respectively) – were selected. The selection was based on easy detectability, low background concentration in the river water and cost and easy availability in local market. The background concentration of the these tracers in the river water was found to be Each one of the above chemicals was dissolved in river water taking into consideration its solubility and the pumpage from the French well to obtain a minimum predetermined concentration of individual tracers, in case a short-circuit channel-type of flow existed from each of tracer injection points to the collector well via infiltration through the radial pipes.
Three tracer injection points were selected in the river bed close to the suspected sources of contamination (Fig. 1): point A near the discharge point of domestic sewage from slum pocket/hutment into the river; point B about 50 m down stream of French well; point C near the discharge point of Duffnala into the river.
A pit of appropriate size of up to a depth of about 0.3 m below the water table was excavated at each of the above selected points in order to inject required volume tracer solution. The amount of tracer added was such that it would give a concentration of at least 20 mg/l above the background level into the water pumped out from the collector well for a period of 24 h, if there existed a short-circuit-type of flow from the injection points to the collector well. The tracer solution was applied in the form of a slug (pulse type of injection; DFR 1994). A large quantity of river water was poured into the pits after dissipation of the tracer solution from the pits into the river bed. This was done to make sure that the tracer from the pits was flushed out properly. About a week prior to the injection of tracer solution all the submersible pumps installed in the French well were switched on to flush out the existing water stored in the collector well. During the tracer experiment, all the radial pipes discharging water into the central collector well were closed except those pointing towards the tracer injection points. The pumping operation was controlled until a steady-state condition of water level in the collector well was achieved. Chlorination of the French well water was also discontinued a week prior to start of the experiment.
Well-water samples were collected to determine the concentration of injected tracers after every 15 min for the first 6 h; after every 30 min for the next 72 h and after every hour for next 85 h. Ion concentration analyses of water from the French well were made using a Dionex 2000i/SP ion chromatograph having a detection sensitivity of less than 100 ppb. Physico-chemical, biological and bacteriological analyses of water samples for every 12 h were also carried out and the results indicated that bacterial contamination is present throughout the duration of the test.
The results of tracer experiment ruled out the existence of any channel type of flow in the river between the points of injection and the collector well. However, bacteriological pollution existed throughout the test in the collector well. Pumping test data indicated that the river bed aquifer is highly anisotropic with horizontal permeability approximately ten times the vertical permeability. Also as long as there is sufficient surface flow in the river so that the pumping from the French well does not deplete the river bed aquifer in its vicinity, the radius of influence is small varying between 150–200 m. However, when the surface water flow in the river bed is small such that most of the water pumped out is derived by dewatering of the river bed aquifer, the radius of influence increases with the rate of pumping and extends well beyond the width of the river channel.
The steady state velocity is so low, less than 100 m/annum, which is why the injected tracer could not be detected in the tracer test and also why the effect of contamination of the river bed was not seen for all these years. Clearly the travel time from the pollution sources (i.e. the sewage discharge points) to the collector well is more than a year. As a result there is to an extent a self-purification mechanism operating in the river bed through the annual monsoon flood. However, if the pollution is persistent and continues year after year with little flow of clean surface water from upstream, the pollution will slowly spread in the river bed aquifer over a time scale of few years. That such a situation has already occurred, has been reported clearly from the physico-chemical and bacteriological analyses of the river bed soil.
The boreholes (BH-1, BH-2, and BH-4) of 10-cm diameter were drilled up to a depth of 12 m in the river-bed stretch near the Sabarmati French well. The borewells are located mid-way between tracer injection points and the French well. The investigations revealed that total coliforms and faecal streptococci bacteria were present almost throughout 12 m depth, that is up to a depth reaching the radial pipes of the collector well. This fact indicated that river bed aquifer had been contaminated by faecal matter due to steady migration of pollution along with the microorganisms from the sewage outfalls. This is also corroborated by the presence of bacteria in the water pumped out from the collector well during the test. Consideration of these results in combination with the tracer studies suggested that the bacterial contamination of the Sabarmati French well was due to a slow but steady build up of the pollution and the microorganisms in the river bed aquifer rather than any event (such as disturbance of the strata) that may have caused a channel-type flow causing direct transmission of the bacteria from the se-

wage outfall to the French well prior to the detection of contamination.

Hydrogeology

Ahmedabad is underlain by thick alluvial deposits of Quaternary age. The geology of the area, which forms part of Cambay basin, has been studied in detail because of exploration for oil and gas. The lithology of deep bore holes drilled by Ahmedabad Municipal Corporation reveals that alluvium comprises of alternating beds of sand, silt, clay and gravel (Gupta and others 1975). Sub-surface section of the river as recorded during construction of several road bridges across the river at Ahmedabad showed that the river bed consists of 10–15-m thick, loosely consolidated, upper sandy aquifer. This sandy layer is underlain by a semi-permeable silt with clay formation (Gupta and others 1975). Several sand layers extend to a depth of about 50 m. These layers are interspersed with lenses of silt and clay but are essentially in direct communication with one another and may be treated as a single unconfined aquifer. A 20–50-m-thick clay layer separates the deeper aquifer (depth more than 100 m) from the unconfined aquifers in most part of the city. Very few pumping test data exist to enable quantitative estimation of aquifer flow and storage characteristics. Desai and others (1979), based on an artificial recharge experiment estimated the coefficients of transmissivity of confined aquifers as 535–645 m^2/day.

Aquifer parameters

A step draw-down pump test was conducted both at Sabarmati Railway bridge and Acher French wells to estimate the radius of influence and to understand the groundwater flow conditions around the collector well. The test was carried out by switching on one pump after another in sequence at an interval of 4 h and simultaneous recording of fall in water level in the central collector well. This experiment continued until all the five pumps became operational taking about 20 h time. After completion of step draw-down test, all the pumps were switched off simultaneously and the recovery of the water level in the well due to infiltration was noted for 24 h. The step drawdown test and recovery test were interpreted by computer simulation model (DFR 1994). The results of the step draw-down pumping test for Sabarmati and Acher Wells together with the simulated pumping draw-down curves using the Hantush and Papadopulos (1962) theory of collector wells. Results indicate that under conditions of continuous pumping, the radius of influence of either of French collector wells is 150 m or more when the river carries sufficient surface flow. However as the surface flow dwindles and the river bed aquifer tends to be de-watered in response to continuous pumping by the French wells, as happens during summer months, the radius of influence extends to more than 1500 m, that is well beyond the width of the river bed. The implication is that it if there is a continuous source of polluted water to the river bed anywhere within the radius of influence of the French collector wells it is likely to find its way by slow percolation through the river bed aquifer into the collector wells.

The permeability of Sabarmati river bed aquifer was estimated by conducting a long-duration pumping test. The permeability and aquifer thickness of Sabarmati French well was estimated as 115 m/day and 18.3 m respectively (Kadiwala 1973). The pumping test data was reinterpreted and results indicated that the river bed aquifer had high anisotropy with vertical permeability being only about 6% of the horizontal permeability (Table 1). Model simulation using the theory of groundwater flow to collector wells (Hantush and Papadopulos 1962) estimated higher permeability of 172 m/day around the French well (Table 1). The hydraulic gradient in the river bed aquifer was assumed as 0.5 m/km and porosity as 0.2. The permeability of formations on either side of Sabarmati river course was assumed 20 m/day. The thickness of first layer was 18.3 m and second layer 10 m.

Boundary condition and input/output stresses

The model area covers about 3000 m × 3000 m and the Sabarmati river flows from north to south in the middle. The width of river is about 500 m around French well near Sabarmati railway bridge, Ahmedabad. Three point sources are (1) Duff-nala stream of Shahibaug on the eastern periphery of the river, (2) sewage discharge from slum pocket on the western periphery and (3) another sewage discharge from hutments south of the French well.

A finite difference grid was used for preparation of groundwater flow, pathlines and mass transport models and the simulated vertical cross-section has two layers (Fig. 3). The collector well is fitted with 16 radial infiltra-

Table 1
Hydrogeological parameters of Sabarmati river bed aquifer estimated from different pumping test interpretation (DFR 1994). A using pump test data of Kadiwala (1973) and considering theory of unconfined aquifers with vertical movement, B and C obtained from pumping test interpretation model no vertical movement

Location	Sabarmati French Well A	Sabarmati French Well B	Acher French Well C
Saturated aquifer thickness (m)	18.3	20.0	17.0
Permeability (m/day)	115	172	90
Ratio of vertical to horizontal permeability (Kz/Kx)	0.06	–	–
Storage coefficient (S)	0.2	0.2	0.2

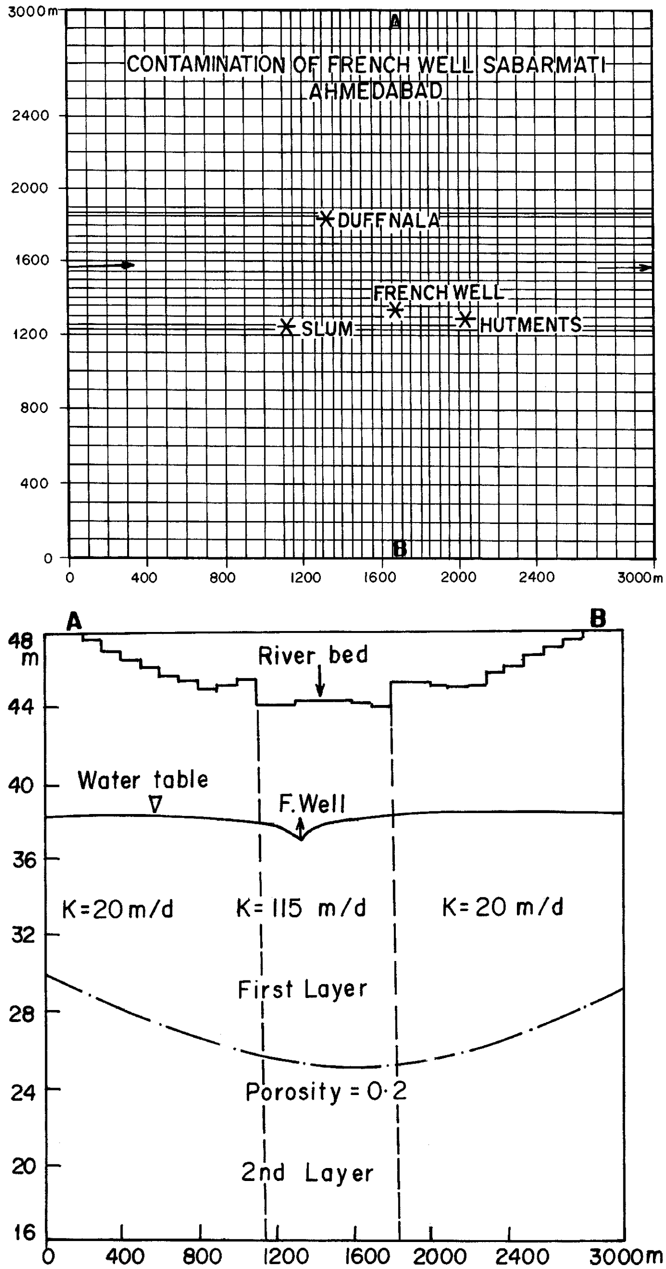

Fig. 3
Finite difference grid and simulated vertical cross-section

tion pipes of lengths varying from 3 to 50 m at a depth of 10–11 m below the river bed (Fig. 4). Groundwater pumping of 4000 m^3/day from the French well was simulated in the model throughout the year. No flow boundary has been assumed to the east and west. Some lateral inflow enters through the north and leaves through south mostly across the river bed. The inflow and outflow at the river nodes were simulated as constant head boundary condition. The Duff-nala stream was located about 600 m from the French well and average sewage discharge was about 300 m^3/day. The seepage of about 100 m^3/day was assumed to the groundwater regime and was accordingly simulated as quantum of input through an injection well. The sewage effluent discharge from slum pocket and hutment sources was about 30 m^3/day each. The seepage from these sources was assumed as 10 m^3/day each and simulated as input to the aquifer system through two injection wells. Local pumping and areal recharge was assumed equal. Thus no areal input/output was simulated in the model.

Groundwater flow and mass transport models

Groundwater heads were computed using visual MODFLOW software (Guiger and Franz 1996; McDonald and Harbaugh 1988). The computed heads were used to calculate groundwater velocities using porosity values in the MODPATH program (Pollock 1989). The groundwater velocity field was coupled to the mass transport model using MT3D software (Zheng 1990). Sewage effluent total dissolved solids (TDS) concentration was in the range of 800–1000 mg/l and at the source locations groundwater TDS concentration reached about 500 mg/l. Groundwater TDS concentration at the source nodes was kept constant at 500 mg/l throughout mass transport simulation. The longitudinal dispersion coefficient of 30 m and a horizontal transverse dispersion coefficient of 10 m was assumed to account for dispersion processes. The model used a daily time step of 365 days. Time dependent pathlines and iso-TDS concentration contours were computed under two different scenarios to determined capture zone and contaminant migration from sources towards the French well.

Dry river bed condition (scenario I)

The steady-state water level and draw-down at the French well was computed as 3.0 m and is found matching closely with observed draw-down. The computed groundwater velocity vectors indicate predominant groundwater flow towards the French well. The predicted pathlines assuming conservative contaminant transport with a retardation factor ($R=1$) indicates the capture zone of French well for 365 days. The capture zone had a radius of about 350–400 m (Fig. 5). The TDS concentration of the contaminant in groundwater for the same period was predicted in mass transport model. The computed iso-concentration contours of TDS indicate areal extent of contaminant from pollutant sources entering the capture zone of French well.

Controlled flow in river (scenario II)

The boundary conditions of river nodes were modified to incorporate river–aquifer interaction assuming controlled release of surface water flow from the Dharoi reservoir in the upstream. The surface water level was assumed to be about 0.2 m above stream bed level along the entire river course. The hydraulic gradient of river water level was

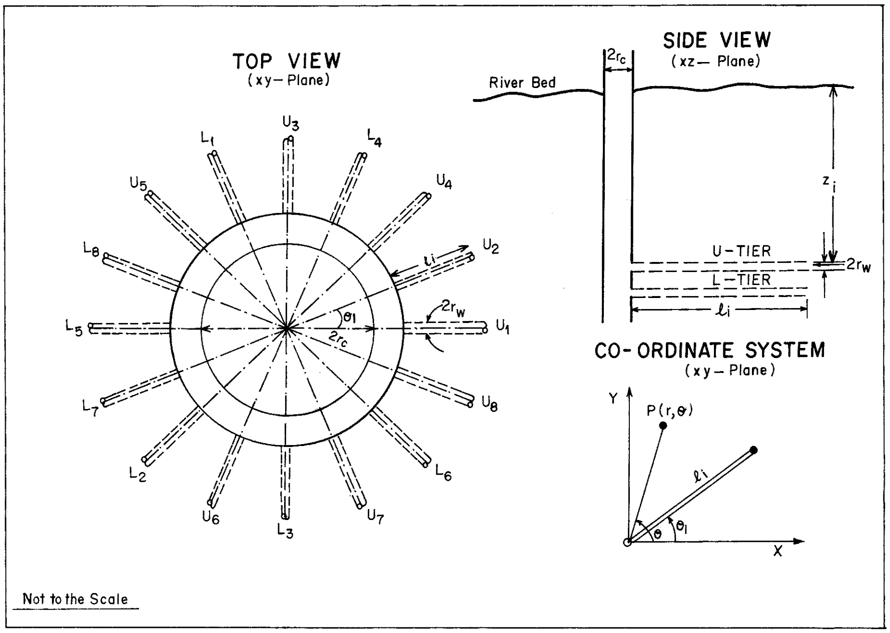

Fig. 4
Schematic diagram of Sabarmati French Collector well

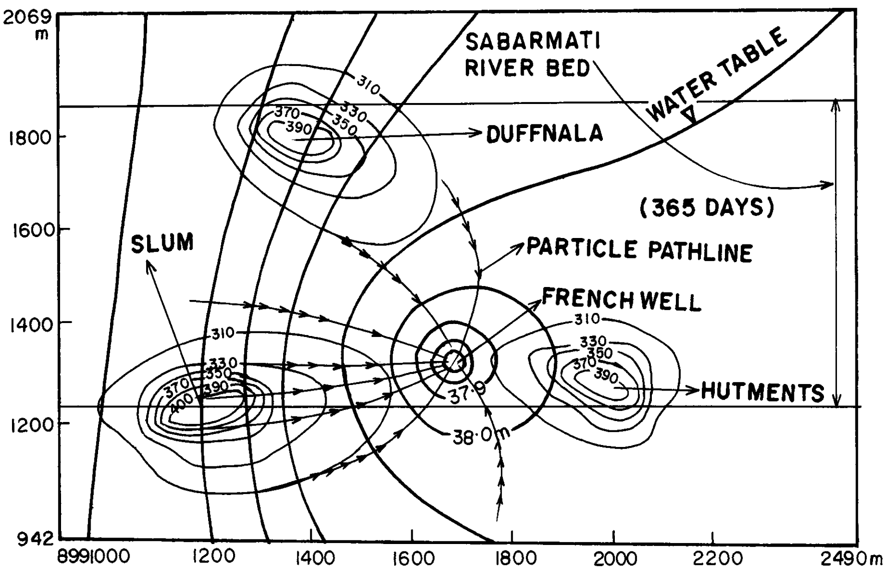

Fig. 5
Computed contaminant migration from sewage sources and capture zone of French well under scenario I – dry river bed

considered while assigning surface water level at the river nodes. The scenario could be implemented by arranging controlled release of surface water from Dharoi reservoir throughout the year. The leakage factor from stream bed to the aquifer was assumed as 0.03 l/day. The output from the model, i.e. pumping from French well and pollutant load from three sources on Sabarmati river bed was kept same as in scenario I.

The computed draw-down around the French well under this scenario was 0.9 m. Groundwater withdrawal of about 85% from the French well was found replenished through river–aquifer interaction. The computed iso-concentration of TDS from the mass transport model indicate decreased levels confined to a small region. In this case, there is no possibility of pollutant particles migrating to the French well capture zone from sources in one year. The length and width of contaminant plume from the three pollutant sources were relatively small (Fig. 6). Comparison of pathlines and iso-concentration contours of TDS under both scenarios indicate that capture zone of the French well under scenario II was much less than under scenario I. The scenario II clearly indicated necessity of providing controlled release of surface water from Dharoi reservoir to maintain a minimum level of 0.2 m surface water around the French well. The scenario could be implemented through appropriate planning of controlled release of surface water from Dharoi reservoir. The significant role of river–aquifer interaction controlling pollutant migration from sewage sources was also evident. Thus, it became imperative for the government

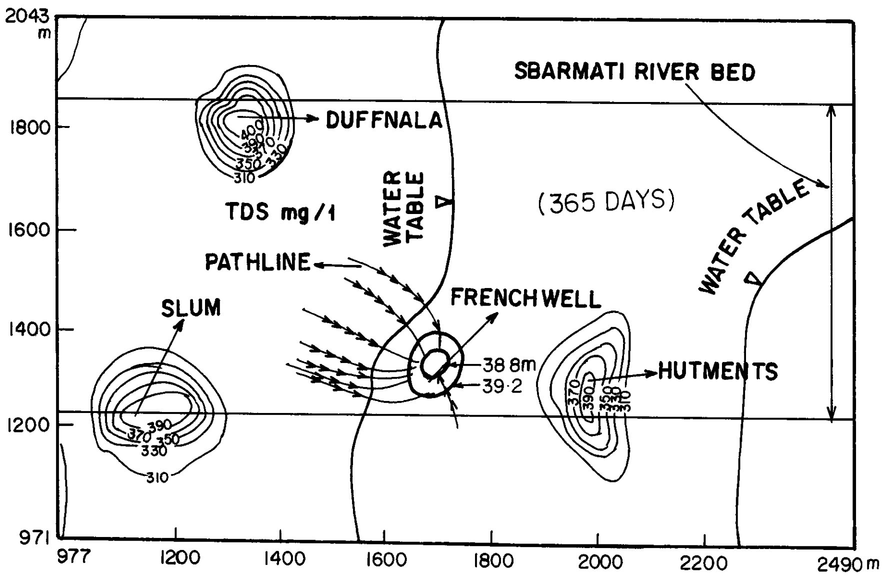

Fig. 6
Computed contaminant migration from sewage sources and capture zone of French well under scenario II – flow in river

to implement a scheme of controlled release of surface water from Daharoi reservoir throughout the year to reduce contaminant migration from sewage sources in this reach of Sabarmati river. The computed radius of influence of French well as 150–200 m in the model when there is flow of surface water in the river and it confirmed pumping test results (DFR 1994). The annual flood flows also dilute surface water contamination. It may take at least more than a year for the contaminant in groundwater to reach French well from the sources, this was reported from tracer experiments (DFR 1994).

Sensitivity analysis

Variation of permeability and porosity values of river bed aquifer was made to assess the importance of each parameter in controlling migration of contaminants from sources to the French well through sensitivity analysis. The permeability value of 172 m/day was computed keeping the same aquifer thickness and capture zone of the French well for 365 days. A lower permeability of 90 m/day was simulated in the model and a corresponding capture zone of French well for 365 days was computed. Comparisons with the calibrated model capture zone revealed that there was no appreciable variation in the size of capture zone for changes in permeability values. Permeability of the river bank aquifer was modified from 20 m/day to 100 m/day in the model and there was no appreciable change noticed in the computed capture zone for 365 days. The second parameter varied was leakage factor between river and aquifer from 0.06 to 0.015 l/day to assess its influence on capture zone. The contaminant migration was closer towards French well, but capture zone remained almost same size. But the variation of porosity value has brought change in size of the capture zone as the groundwater velocity was dependent on it.

Discussion of results

The model computations were made with an uniform permeability of 115 m/day for the river bed aquifer. The extent of the computed capture zone of French well was not appreciably changed even for permeability values of 172 m/day or 90 m/day. The maximum draw-down around the French well for different permeability values was computed (Table 2). The change in average groundwater velocity was found to be very small under different permeability values. This might be due to minor variations that might have resulted in hydraulic gradient for changes in permeability values. The permeability of river bank aquifer does not have much influence on the river bed aquifer. This feature clearly illustrated that drawdown due to pumping from the French well was mainly confined to the 500 m width of the river bed aquifer only. However, it was noticed that significant changes in velocity field would occur for variations in porosity value that will control the migration of contaminant and also the capture zone of the French well. Thus it seems important to estimate porosity value more precisely in the river bed aquifer.

Table 2
Comparison of computed draw-down (in m) at French collector well for different permeability values of river bed aquifer

River bed aquifer permeability (m/day)	Scenario I	Scenario II
172	2.0	0.6
115	2.5	0.9
90	2.6	1.0

Conclusion

A well-head protection area that was delineated by using a time-of-travel criterion was equivalent to a time-related capture zone. The time-related capture zone was smaller for sorbing solutes than for conservative ones. The assumption of conservative solute transport leads to a conservative estimate for computation of size of sought well-head protection area. The predicted capture zone around the French well will be somewhat larger in the present case. If sorption property of the contaminant was known, one can use an appropriate retardation factor to account for adsorbing properties of the aquifer material while computation of actual capture zone. The predicted capture zone of French well under controlled release of surface water from the Dharoi reservoir was small compared to capture zone under dry river bed conditions. The average groundwater velocity of the river bed aquifer under both conditions is in the range of 50–145 m/year. Continuous pumping at a rate of 4000 m^3/day will be sustained if surface water flow was maintained around the French well. The capture zone of French well under dry river bed conditions has a radius of about 300 m. There was no preferred flow pathways in the river bed aquifer for contaminant migration from three sewage sources. The required travel time for contaminants to reach the capture zone of collector well from pollutant sources was more than a year. This confirmed the tracer test results conducted in the area (DFR 1994). As such, there seems to be some self-purifying mechanism operating in the river bed aquifer through the monsoon flood every year. The contaminant migration may be considerably retarded due to filtration, adsorption and decay mechanisms. However, persistent pollution of Sabarmati river bed around the French well could be avoided. There is a immediate need for controlled release of surface water from the Dharoi reservoir to arrest depleting water levels in the river bed aquifer due to pumping from French wells. This will help arresting migration of contaminants from three pollutant sources around the French well.

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